

Spontaneous CP Violation in Large Extra Dimensions

Yutaka Sakamura*

*Department of Physics, Tokyo Institute of Technology
Oh-okayama, Meguro, Tokyo 152-8551, Japan*

Abstract

We show that in the context of large extra dimensions enough CP violation can be obtained from the spontaneous breaking in a simple non-SUSY model, which is usually considered not to cause the spontaneous CP violation. We estimate ϵ_K in our scenario to be of order 10^{-3} consistent with the experimental value. We also propose a modification to the see-saw mechanism and axion scenario to match with our model.

1 Introduction

String theory indicates the existence of extra dimensions beyond our usual four dimensional spacetime. These extra dimensions must be compactified by small radii in order not to be observed. However, these radii do not have to be close to the Planck length, but have only to satisfy the constraint from the gravity experiment, i.e., they should be shorter than cm range. The relation between the fundamental scale M_* and the observed Planck scale M_p is given by

$$M_p^2 = M_*^{n+2} V_n,$$

where V_n is a volume of the extra space, and n is the number of the extra dimensions. If M_* is set to TeV scale, n must be greater than one, otherwise the gravity would change over the scale of the solar system from the observed one.

For simplicity, we assume that the shape of the extra space is torus, in which case $V_n = (2\pi)^n R_1 R_2 \cdots R_n$, where R_i is the radius of the i -th extra dimension. Hence,

$$M_p^2 = (2\pi)^n M_*^{2+n} R_1 R_2 \cdots R_n. \quad (1)$$

We can see from Eq.(1) that M_* can be lowered from M_p to TeV scale by taking the radii R_i to be large compared to the Planck length. In this way, we can solve the hierarchy problem without supersymmetry (SUSY) or technicolor [1, 2].

We can take the standard model (SM) fields for either bulk fields or boundary fields, which are confined to the D-branes or Domain walls. In the case that the SM fields feel some extra dimensions, their compactification scale must be larger than a few hundred GeV because corresponding Kaluza-Klein (K.K.) modes have never been observed yet [3].

It is possible to realize the hierarchy among the fermion masses by using the ratio of the volume of the region in which the bulk fields spread out to that of the boundary fields [4].

*Email: sakamura@th.phys.titech.ac.jp

Q_1	2	U_1	2	D_1	1	L_1	2	E_1	2	H	0	A_1^μ	2
Q_2	1	U_2	1	D_2	1	L_2	1	E_2	1	S	1	A_2^μ	2
Q_3	0	U_3	0	D_3	1	L_3	1	E_3	0			A_3^μ	2

Table 1: The number of the extra dimensions that each field can feel. A_i^μ ($i = 1, 2, 3$) are gauge fields.

CP is a very good symmetry, but it is violated in the $K-\bar{K}$ system by a small amount ($\epsilon_K \simeq 2 \times 10^{-3}$). There are two possibilities for the origin of the CP violation. One is the explicit CP violation, and the other is the spontaneous CP violation (SCPV). In string theory, CP is a gauge symmetry [5, 6], so it must be spontaneously broken. If this CP breaking scale is low enough, one finds that CP is violated spontaneously in an effective field theory at low energy. We shall consider this case here.

In this paper we shall assume that different fields feel different numbers of extra dimensions, as discussed in Ref.[4], and show in the context of large extra dimensions enough CP violation can be obtained from the spontaneous breaking in a simple non-SUSY model, which is usually considered not to cause the SCPV.

In Section 2, we shall explain our model and realize the hierarchy among the fermion masses. In Section 3, we shall estimate ϵ_K in our model and show that it is consistent with the observed value. In Section 4, the neutrino masses and mixing angles are derived without a help of intermediate scale, and in Section 5 we shall try to apply the axion scenario to our context. Finally, Section 6 contains some conclusions.

2 Model

2.1 Our model

Basically, we shall consider the minimal standard model with an additional gauge-singlet scalar field, but we shall assume that different fields feel different numbers of extra dimensions. The relevant interactions are as follows.

$$\begin{aligned}
\mathcal{L}_{\text{int}} = & h_{ij}^u Q_i H^\dagger \bar{U}_j + h_{ij}^d Q_i H \bar{D}_j + h_{ij}^e L_i H \bar{E}_j \\
& + \hat{y}_{ij}^u S Q_i H^\dagger \bar{U}_j + \hat{y}_{ij}^d S Q_i H \bar{D}_j + \hat{y}_{ij}^e S L_i H \bar{E}_j + h.c. \\
& + (\text{Higgs sector}),
\end{aligned} \tag{2}$$

where Q_i , \bar{U}_i and \bar{D}_i are the i -th generation of the left-handed quark doublet, right-handed up-type quark singlet and right-handed down-type quark singlet, respectively. L_i and \bar{E}_i are the i -th generation of the left-handed lepton doublet and right-handed charged lepton singlet. H and S are the doublet and singlet Higgs fields respectively, h_{ij}^x ($x = u, d, e$) are the Yukawa coupling constants and \hat{y}_{ij}^x are dimensionful coupling constants.

Note that the non-renormalizable terms in the second line of Eq. (2) should be considered because the fundamental scale M_* is relatively low in our scenario.

We assume the CP-invariance for the Lagrangian, so that all parameters in Eq. (2) are real. We will explore the possibility that the CP-invariance is broken spontaneously at the weak scale due to the complex vacuum expectation values (VEVs) of the Higgs fields.

The numbers of the extra dimensions that each field can feel are listed in Table 1.

The radii of these extra dimensions are supposed to be the same size and it is denoted by R_1 .

2.2 Fermion mass hierarchy

Let us denote $\psi(x, y)$ as a five dimensional bulk field, where y represents the coordinate of the fifth dimension compactified by a radius R . If we Fourier expand

$$\psi(x, y) = \sum_{m=0}^{\infty} \frac{1}{\sqrt{2\pi R}} \psi_m(x) e^{i(m/R)y},$$

then we can regard $\psi_m(x)$ as a four dimensional field corresponding to the m -th K.K. mode.

On the other hand, the boundary fields are localized at the four dimensional wall whose thickness is of order M_*^{-1} , so a coupling including at least one boundary field is suppressed by a factor ϵ^k , where $\epsilon \equiv 1/\sqrt{2\pi M_* R}$ and k is a number of bulk fields included in the coupling [7]. Generalization to our six dimensional case is trivial.

The existence of infinite K.K. modes change the running of the gauge coupling constants above the compactification scale R_1^{-1} to the power-law running [8]. So, it seems natural that a new physics like the GUT appears up to one order above the scale R_1^{-1} by considering the runnings of the gauge couplings [9]. We shall denote the scale that the new physics appears as M_{NP} .

Now Let us assume that coupling constants h_{ij}^x, \hat{y}_{ij}^x are generated at the scale M_{NP} , then it seems natural that they are of the form as \tilde{h}_{ij}^x/M_{NP} and $\tilde{y}_{ij}^x/M_{NP}^3$ in the six dimensional bulk spacetime, where \tilde{h}_{ij}^x and \tilde{y}_{ij}^x are dimensionless couplings.

In this case the four dimensional couplings h_{ij}^x and \hat{y}_{ij}^x are of the form as

$$h_{ij}^u \simeq \begin{pmatrix} \epsilon^4 & \epsilon^3 & \epsilon^2 \\ \epsilon^3 & \epsilon^2 & \epsilon \\ \epsilon^2 & \epsilon & 1 \end{pmatrix}, \quad h_{ij}^d \simeq \epsilon \begin{pmatrix} \epsilon^2 & \epsilon^2 & \epsilon^2 \\ \epsilon & \epsilon & \epsilon \\ 1 & 1 & 1 \end{pmatrix}, \quad h_{ij}^e \simeq \epsilon \begin{pmatrix} \epsilon^3 & \epsilon^2 & \epsilon \\ \epsilon^2 & \epsilon & 1 \\ \epsilon^2 & \epsilon & 1 \end{pmatrix}$$

$$\hat{y}_{ij}^x \simeq \frac{\epsilon M_*}{M_{NP}^2} h_{ij}^x \quad (3)$$

Here we have assumed $(M_*/M_{NP})\tilde{h} \simeq 1$ and $\tilde{h} \simeq \tilde{y}$. Thus, setting $\epsilon \equiv 1/\sqrt{2\pi M_* R_1}$ to be 1/15, the desired hierarchy among quark and lepton masses and mixing angles are obtained.¹ For example, if we assume $R_1^{-1} \simeq 300$ GeV, we should set $M_* \simeq 10$ TeV. We shall take these values in the following, and further we shall assume $M_{NP} \simeq 3$ TeV.

3 CP violation

CP invariance is broken at the weak scale due to the complex VEVs of the neutral Higgs fields. These VEVs are parametrized as

$$\langle H^0 \rangle = v, \quad \langle S \rangle = w e^{i\rho},$$

where $v = 174$ GeV, and we have removed the phase of the $\langle H^0 \rangle$ by using the $U(1)_Y$ gauge symmetry. Here note that our scenario does not depend on the Higgs potential, so we shall assume the potential to have a CP violating minimum.

¹Since the energy range of the power-law running is much smaller than the hierarchy between M_* and $(2\pi R_1)^{-1}$, the power-law running of the Yukawa couplings does not destroy the structure represented by Eq.(3).

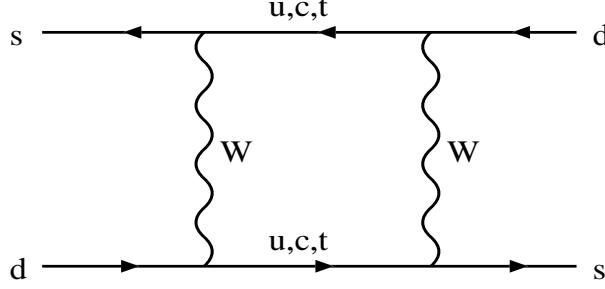


Figure 1: Dominant contribution to $\text{Re}M_{12}$.

Then the quark mass matrices at low energy are obtained as

$$\begin{aligned}(M_u)_{ij} &= (h_{ij}^u + \hat{y}_{ij}^u w e^{i\rho})v, \\ (M_d)_{ij} &= (h_{ij}^d + \hat{y}_{ij}^d w e^{i\rho})v.\end{aligned}$$

We can see from Eq.(3) that M_u and M_d have complex phases of order $\varphi \equiv \epsilon w M_*/M_{NP}^2 \simeq 0.03$, so each element of the CKM matrix also has an $O(\varphi)$ phase. Here we have assumed $w \simeq 200$ GeV.

Next we expand the neutral Higgs fields around their VEVs as follows.

$$\begin{aligned}H^0 &= v + \frac{1}{\sqrt{2}}\phi, \\ S &= w e^{i\rho} + \frac{1}{\sqrt{2}}e^{i\rho}(X + iY),\end{aligned}\quad (4)$$

where we have chosen the unitary gauge. ϕ and X are CP-even real scalar fields, and Y is a CP-odd one.

In terms of these fields, renormalizable Yukawa coupling terms below the weak scale are

$$\begin{aligned}\mathcal{L}_{\text{Yukawa}} &= \frac{m_i^u}{\sqrt{2}v_2}q_i\bar{u}_i\phi + \frac{m_i^d}{\sqrt{2}v_1}q_i\bar{d}_i\phi \\ &+ \frac{1}{\sqrt{2}}\hat{y}_{ij}^u e^{i\rho}q_i\bar{u}_j(X + iY) + \frac{1}{\sqrt{2}}\hat{y}_{ij}^d e^{i\rho}q_i\bar{d}_j(X + iY) \\ &+ (\text{lepton sector}),\end{aligned}\quad (5)$$

where q_i , u_i and d_i are the mass eigenstates of quarks, and m_i^x is the mass eigenvalue corresponding to the state x_i . Note that $y_{ij}^u \equiv \hat{y}_{ij}^u v$ and $y_{ij}^d \equiv \hat{y}_{ij}^d v$ have $O(\varphi)$ phases, where $\hat{y}^{x'}$ is the \hat{y}^x -matrix in the basis of the quark mass eigenstates.

Now we shall estimate ϵ_K in the K - \bar{K} system. The CP violation parameter ϵ_K can be expressed as [10, 11],

$$|\epsilon_K| \simeq \frac{1}{2\sqrt{2}} \frac{\text{Im}M_{12}}{\text{Re}M_{12}}, \quad (6)$$

where M_{ij} is the neutral kaon mass matrix in the $K^0 - \bar{K}^0$ basis.

The dominant contribution to $\text{Re}M_{12}$ comes from the standard box diagram depicted in Fig.1.

This diagram is estimated as [12]

$$\begin{aligned}M_{12}^{\text{box}} &= \frac{G_F}{2\sqrt{2}} \frac{\alpha}{4\pi \sin^2 \theta_W} (\cos \theta_c \sin \theta_c)^2 \left(\frac{m_c^2}{M_W^2} \right) \frac{\langle K^0 | \bar{d}_L \gamma_\mu s_L \bar{d}_L \gamma^\mu s_L | \bar{K}^0 \rangle}{M_K} \\ &\simeq 10^{-13} \cdot \frac{\langle K^0 | \bar{d}_L \gamma_\mu s_L \bar{d}_L \gamma^\mu s_L | \bar{K}^0 \rangle}{M_K} \quad (\text{GeV}^{-2}),\end{aligned}\quad (7)$$

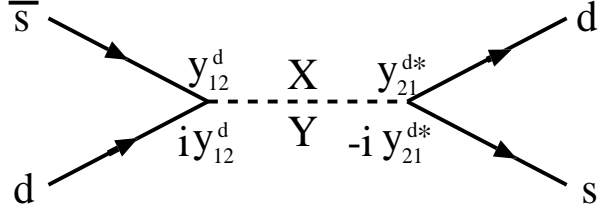


Figure 2: Dominant contribution to $\text{Im}M_{12}$.

where m_c , M_W and M_K are the masses of the c quark, W boson and the kaon respectively, and G_F and α are the Fermi constant and the fine structure constant. θ_W and θ_c are the Weinberg angle and the Cabibbo angle respectively.

On the other hand, the dominant contribution to $\text{Im}M_{12}$ comes from the tree-level diagram shown by Fig.2, because the box diagram mentioned above is real up to the phase of order φ and cannot be the leading contribution.

This contribution is calculated by [12]

$$\begin{aligned} M_{12}^{\text{tree}} &= \frac{y_{12}^d y_{21}^{d*}}{M_S^2} \frac{\langle K^0 | \bar{d}_L s_R \bar{d}_{RSL} | \bar{K}^0 \rangle}{M_K} \\ &\simeq \left(\frac{v M_*}{M_{NP}^2} \right)^2 \frac{\epsilon^7}{M_S^2} \frac{\langle K^0 | \bar{d}_L s_R \bar{d}_{RSL} | \bar{K}^0 \rangle}{M_K}, \end{aligned} \quad (8)$$

where M_S is the mass of the singlet Higgs field.

According to Ref.[12],

$$\frac{\langle K^0 | \bar{d}_L s_R \bar{d}_{RSL} | \bar{K}^0 \rangle}{\langle K^0 | \bar{d}_L \gamma_\mu s_L \bar{d}_L \gamma^\mu s_L | \bar{K}^0 \rangle} \simeq 7.6, \quad (9)$$

then

$$\left| \frac{M_{12}^{\text{tree}}}{M_{12}^{\text{box}}} \right| \simeq 10^{13} (\text{GeV}^2) \left(\frac{v M_*}{M_{NP}^2} \right)^2 \frac{\epsilon^7}{M_S^2} \times 7.6 \simeq 2 \times 10^9 \left(\frac{v M_*}{M_{NP}^2} \right)^2 \epsilon^7. \quad (10)$$

Here we have assumed $M_S \simeq 200 \text{ GeV}$.

Together with the fact that $\text{Arg}(M_{12}^{\text{tree}}) = O(\varphi)$,

$$|\epsilon_K| \simeq \frac{1}{2\sqrt{2}} \cdot \varphi \cdot \left| \frac{M_{12}^{\text{tree}}}{M_{12}^{\text{box}}} \right| \simeq \frac{1}{\sqrt{2}} \cdot 10^9 \cdot \epsilon^8 \left(\frac{v}{M_{NP}} \right)^2 \frac{w}{M_{NP}^2} \left(\frac{M_*}{M_{NP}} \right)^3 \simeq 10^{-3}. \quad (11)$$

4 Neutrino

In our scenario, the fundamental scale M_* is of order TeV scale, so at first sight it does not seem that the see-saw mechanism, which requires an intermediate scale around 10^{10} GeV , can be applied. However, by using the volume factor suppression mentioned in Section. 2.2 we can realize the small masses of the neutrinos.

We shall introduce a new extra dimension and denote its radius as R_2 . Let the right-handed neutrinos ν_{Ri} ($i = 1, 2, 3$) feel this new extra dimension, so that neutrino Yukawa couplings h_{ij}^ν are suppressed by a large volume factor $1/\sqrt{2\pi M_* R_2}$ and the Dirac masses of neutrinos can become small enough [7, 13].

Denote the Majorana mass scale of the right-handed neutrino as M_N , then according to the see-saw mechanism left-handed neutrino mass matrix m_ν is calculated

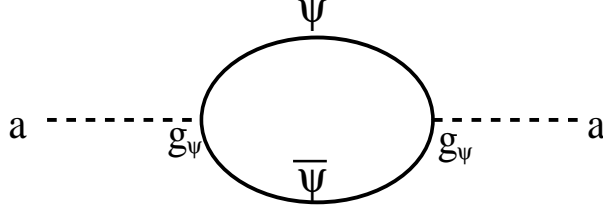


Figure 3: Relevant diagram to Z_a .

as,

$$m_\nu \simeq \frac{v^2}{M_N} \frac{1}{2\pi M_* R_2} \begin{pmatrix} \epsilon^2 & \epsilon & \epsilon \\ \epsilon & 1 & 1 \\ \epsilon & 1 & 1 \end{pmatrix}, \quad (12)$$

where $v = 174$ GeV. This realizes the large mixing between ν_μ - ν_τ expected from the atmospheric neutrino and the small mixing between ν_e - ν_μ expected from the small angle MSW solution simultaneously [4].

For example, if we assume $M_N \simeq M_*$, we should set $R_2^{-1} \simeq 2$ keV in order to obtain $m_{\nu_\tau} \simeq 10^{-1}$ eV.

We shall list some notable comments.

First, if we try to suppress m_ν only by the volume factor without the see-saw mechanism, then R_2 becomes so large that the extra dimension will be observed by the gravity experiment. Thus we must either use the see-saw mechanism or let ν_{Ri} feel more than one extra dimensions in order to realize the experimentally accepted small masses of the neutrinos without contradiction to the gravity experiments.

Second, the effect of the running of h_{ij}^ν between M_{NP} and R_2^{-1} is not expected to be very large by the same reason mentioned at the footnote in Section.2.2. Then we have neglected this running effect in the above discussion.

Finally, it is worthy to note that the infinite Kaluza-Klein modes of ν_{Ri} can correspond to the sterile neutrinos from the phenomenological point of view [13].

5 Strong CP problem

The axion scenario is the most convincing solution to the strong CP problem. Similarly to the previous section, however, the axion scenario also needs the intermediate scale that the Peccei-Quinn symmetry is broken at. Here we shall avoid this difficulty by using the power-law running of coupling constants, which is characteristic of the context of large extra dimensions.

Assume that the axion, which is confined to our four dimensional wall, interacts with spinor fields ψ and $\bar{\psi}$, which feel two extra dimensions whose radii are both R_3 .

$$\mathcal{L}_{a\psi\bar{\psi}} = g_\psi a \psi \bar{\psi},$$

where a represents the axion field.

In this case a wavefunction renormalization factor of the axion Z_a will scale according to the power-law running above the scale $\mu_3 \equiv R_3^{-1}$.

$$Z_a = 1 - c g_\psi^2 \left(\frac{\Lambda}{\mu_3} \right)^4 + \dots, \quad (13)$$

where $a(\Lambda) = Z_a^{1/2} a(\mu_3)$, Λ is a cut-off and c is an $O(1)$ constant.

$$g_\psi(\Lambda) = Z_{a\psi\bar{\psi}} Z_a^{-1/2} Z_\psi^{-1/2} Z_{\bar{\psi}}^{-1/2} g_\psi(\mu_3), \quad (14)$$

where $Z_{a\psi\bar{\psi}}$ is a vertex renormalization factor, Z_ψ and $Z_{\bar{\psi}}$ are wavefunction renormalization factors of ψ and $\bar{\psi}$ respectively.

Here if we assume that the power-law running of Z_a is the strongest of the runnings of the Z -factors, then

$$g_\psi^{-2}(\Lambda) \simeq \left\{ 1 - c g_\psi^2 \left(\frac{\Lambda}{\mu_3} \right)^4 \right\} g_\psi^{-2}(\mu_3). \quad (15)$$

Next we put another assumption that the value of g_ψ at the Peccei-Quinn symmetry breaking scale (PQ scale) M_{PQ} is much larger than $g_\psi(\mu_3)$. Then we obtain

$$g_\psi(\mu_3) \simeq \left(\frac{\mu_3}{M_{PQ}} \right)^2. \quad (16)$$

From the assumption, this suppression mainly comes from the power-law running of Z_a , so that all couplings including the axion field a are expected to receive the same suppression factor as that of g_ψ . For example, the coupling $-(1/64\pi^2)(a/M_{PQ})\epsilon_{\mu\nu\rho\sigma}F_\alpha^{\mu\nu}F_\alpha^{\rho\sigma}$ receives the suppression factor $(\mu_3/M_{PQ})^2$ below the scale μ_3 , thus effective PQ scale f_{PQ} becomes

$$f_{PQ} \simeq \left(\frac{M_{PQ}}{\mu_3} \right)^2 M_{PQ}. \quad (17)$$

For instance, if we set $M_{PQ} \simeq M_*$ and $\mu_3 = 10$ GeV, then we shall obtain $f_{PQ} \simeq 10^{10}$ GeV and this value satisfies the cosmological constraint.²

6 Conclusions

We showed in the context of the large extra dimensions enough CP violation can be obtained from the spontaneous breakdown in a simple non-SUSY model, which is usually considered not to cause the spontaneous CP violation and estimated ϵ_K to be of order 10^{-3} consistent with the experimental value. It is appealing that the same volume factors are used to generate both adequate smallness of the CP violation and the hierarchy among Yukawa couplings, which is used to suppress the flavor changing neutral current (FCNC).

Our scenario does not depend on the Higgs potential that has a CP violating minimum and no extra symmetries are introduced, so we can easily generalize our model to models with more complicated Higgs sector. For example, two-Higgs-doublet standard model with the exact discrete symmetry of natural flavor conservation can also cause the SCPV in our scenario. The essence of our scenario is the existence of the suppressed extra Yukawa matrices that have complex phases and become main sources of the CP violation. Another work in this direction is, for example Ref.[11], in which extra Higgs doublets are introduced and Peccei-Quinn-like approximate symmetry are used to suppress the dangerous FCNC and the CP violation to the observed level. On the other hand, we have used the volume factor suppression in the context of large extra dimensions instead of some approximate symmetries.

In our scenario, naive see-saw mechanism or axion scenario, which need an intermediate scale around 10^{10} GeV, cannot be applied since the fundamental scale M_* is TeV scale. However, these difficulties can be avoided by making use of the volume factor suppression or the power-law running of couplings, which are characteristic of the context of large extra dimensions.

²In Ref.[14] the axion field itself is suppose to be the bulk field and the constraint: 10^9 GeV $<$ f_{PQ} $<$ 10^{15} GeV is satisfied by the volume factor suppression.

One can also consider the scenario that the Yukawa couplings are generated at the scale M_* and realize the hierarchy among the Yukawa couplings as the hierarchy among quasi infrared fixed points (QFPs) [17], but in such a case the coupling constants \hat{y}_{ij}^x would become too small to realize the realistic value of ϵ_K . Also, in this case M_{NP} has to be lift up to M_* , we would need some mechanism that suppresses the power-law running of the gauge coupling constants, for example N=4 SUSY.

So far we have not assumed supersymmetry because SUSY models have so many sources of the CP violation that the observed CP violation can be obtained without our scenario. However our scenario can be applied in SUSY models if we adopt an appropriate SUSY breaking mechanism (for example Scherk-Schwarz mechanism [15, 16]) in which super-particles are heavy enough, squark masses are degenerate and so on. In this case, we can say that our scenario extends the parameter space that gives the observed CP violation in the SCPV.

We collect the example values of all scales used here,

$$R_2^{-1} \simeq 2 \text{ keV}, \quad R_3^{-1} \simeq 10 \text{ GeV}, \quad \langle S \rangle \simeq 200 \text{ GeV}, \quad R_1^{-1} \simeq 300 \text{ GeV}, \\ M_{NP} \simeq 3 \text{ TeV}, \quad M_N \simeq M_{PQ} \simeq M_* \simeq 10 \text{ TeV}.$$

Of course, there are various other possibilities for their values.

Here we introduced new five extra dimensions. These must satisfy the relation Eq.(1). In the case of $n = 6$, which is motivated by the superstring theory, the remaining radius is about $(4 \text{ MeV})^{-1}$ and satisfies the constraint from the gravity experiment.

If we suppose our scenario to be right, we can represent each scale as a function of R_1^{-1} .

$$M_* \simeq 36 R_1^{-1}, \quad M_{NP} \simeq 1.8 \times 10^2 R_1^{-1/2}, \quad R_2^{-1} \simeq 2.7 \times 10^{-11} R_1^{-2}, \\ R_3^{-1} \simeq 2.1 \times 10^{-3} R_1^{-3/2}, \quad R_4 \simeq 1.4 \times 10^{-5} R_1^{-1}, \quad (18)$$

where the unit is GeV, and R_4 is the remaining radius in the case of $n = 6$.

Of course, the hierarchy among the radii of the extra dimensions, which is assumed here, must be explained for completeness.

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